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A LARGE MOORED TRIPOD STRUCTURE FOR THE DEEP OCEAN

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ABSTRACT

A large, moored tripod oceanographic measurement structure was fabricated and deployed in the deep ocean. The structure was 5100 m high with a base footprint of 6190 m, all suspended by a single 6150-lb buoyant float. The three 6200-m-long legs contained environmental measurement instrumentation in the top 2150 m of each leg. A lightweight cable design facilitated storage, deployment, and retrieval of more than 27,700 m (15 nmi) of cable and mooring from a relatively small, 210-ft-long tending vessel. Communications with the system was via a single 9100-m-long steel coaxial cable, which also moored the tending vessel during operation. Each leg was moored to the bottom with a 7000-lb anchor. The equipment was deployed in the most efficient way possible to allow this single tending vessel to transport and deploy over 67 tons of system equipment. This paper focuses on describing the mooring hardware components and the techniques for deploying this large, moored, tripod structure.

INTRODUCTION

The U.S. Navy has the need to deploy large measurement systems for monitoring deep-ocean environmental parameters. Some of these systems must span the complete water column and provide a stable structure for performing the measurements. Such a system was required for a summer 1991 experiment. This led to the development, testing, and operation of a buoyed, suspended, three-legged tripod structure that was 5100 m high and had a base footprint of 6190 m.

A 1971 Navy program fostered the fabrication and deployment of a system of this magnitude. This program focused on developing components and techniques that would meet these explicit measurement system requirements. Two major results of the effort were the Kevlar instrumented cables and the torque-free, lightweight steel coaxial cables commonly used today.

Although many instrumented structures used this evolving technology base in the ensuing years, the Navy's vertical instrumented cable system deployed in 1988–1989 clearly demonstrated the feasibility of future volumetric structures at modest cost and deployment scenarios. This earlier system consisted of a single moored vertical instrumented cable, which spanned the water column in 5200 m of water, a mass weight anchor, and 9100 m of 0.69 in. spaced armor coaxial umbilical cable. This cable provided the functions of lowering the

anchor to the sea floor, mooring the structure to the tending vessel, and communicating with the instrumented cable system. The actual experiment demonstrated the feasibility of deploying multiple legs utilizing the same components and procedures.

The 1991 summer experiment employing the tripod structure was preceded by a series of three at-sea engineering tests.[1] These tests were performed to develop the procedures and evaluate the hardware prior to the experiment. The initial test was the deployment of a 1/3-scale system. This test defined the deployment scenario and evaluated the deployment vessel and machinery. The second test was the evaluation of an anchor navigation system. This system was employed to place the leg anchors precisely at predesignated locations. The final test was a full-scale dress rehearsal to refine the deployment/retrieval procedures and to test all major system components. This test was conducted at the same Atlantic location planned for the experiment. Environmental assessments[2,3,4] of the site provided an insight to the expected conditions.

Numerous contingencies were incorporated into the final deployment plan as a result of this triple-test program. These contingency plans included such obvious things as actions to be taken due to adverse weather, ship equipment failure, structure component failure, instrumentation failure, navigation failure, high surface currents, ship delays, etc. These anticipated actions were supported by a suite of back-up equipment and spares.

The experiment was conducted during June/July 1991 in the Sargasso Sea. The at-sea portion (port-to-port) lasted 25 days, with the measurement period covering 11 days.

GENERAL SYSTEM DESCRIPTION

Structure

Figure 1 shows the tripod structure configuration and the support systems. The length of the three legs is equal, 6200 m long. They are suspended by a single apex buoy. The top 2150 m of each leg is the instrumented cable sections. The lower sections of legs 2 and 3 are mooring lines attached to the anchors. Leg 3 has 4050 m of coaxial lead-in between the instrumented cable section and the anchor. A spaced armor coaxial umbilical cable

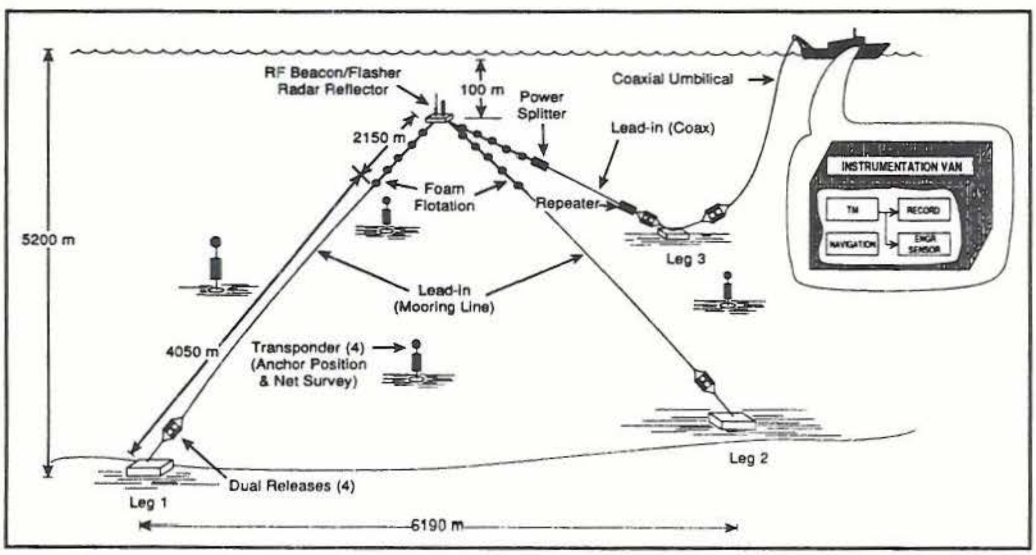

Figure 1. Moored tripod system.

runs from the leg 3 anchor to the tending vessel. This cable provides the communication link with the system and also moors the tending ship during the operation. The legs are rendered slightly positively buoyant with syntactic foam blocks that have been distributed along their length.

Anchor Navigation System

An anchor navigation system was employed to place each anchor at a specific location during the deployment operation. The placement of the anchors controls the tilt angle and orientation of the structure's leg. An anchor separation of 6190 m and an apex buoy depth of 100 m resulted in an approximate 35° tilt angle referenced to vertical. A series of four transponders was deployed. Precise position was determined prior to the system deployment. These transponders operated in conjunction with the dual acoustic releases located at the anchors. The releases operated as transponders to allow precise anchor placement. This navigation net also tracked the tending vessel during the deployment. The system was operated in conjunction with the global positioning system to provide geodetic positioning. This system allowed us to place the anchors to within less than 100 m of the desired locations.

Communications System

The communications system was a multichannel data acquisition system. It was designed to acquire calibrated data at full ocean depth and to telemeter these data to a surface platform. The telemetry system included the hardware to communicate with the structure, record the data, and perform real-time data quality checks. The communications hardware included multiplexers, demultiplexers, lead-in (coax) cable, umbilical cable, down-up link command control, power conditioners, power splitter, and signal repeater. The power splitter, located on leg 3, incorporated the provision for independent power/signal paths for each leg. This provision reduced the risk of losing power in the complete system if seawater leaked in any one leg. A signal repeater, also located on leg 3, was compensated for the signal attenuation in the long cable paths (up to 15,000 m long).

Engineering Sensors

A suite of engineering sensors was distributed along each leg to determine the physical orientation and configuration of the structure. The two types of sensors were shape and tension. The shape sensor measured two-dimensional tilt, heading, pressure, temperature, and seawater conductivity. The tension sensors measured the leg tension through in-line load cells at the top and bottom of each leg. Data from these sensors allowed near-real-time determination of the structure's engineering characteristics.

A more detailed description of the major subsystems overviewed in this section can be obtained in Reference 1.

MOORING COMPONENTS DESCRIPTION

Cable System

The Kevlar instrumentation cable (Figure 2) was fundamental in making the instrumented structure feasible within many interlocking constraints, such as cost, time, deployment vessel and machinery, staffing, etc. This free-flooding, 0.95-in-diameter Kevlar 29 cable had a breaking strength in excess of 20,000 lb, an in-water weight of 0.33 lb/m, and a maximum stretch of only 0.6 of 1% at its deployed tension. In addition, it was equipped with a filament fairing to suppress strumming. Conductors were easily accessed anywhere along their lengths for sensor placement and were terminated with a simple Kevlar grip. The resulting structure cable could be easily coiled in coiling tanks with a minimum 3-ft diameter, which in turn provided for water-bath testing and storage.

A similar lead-in transmission cable (Figure 3) used a single 0.56-in-diameter coax, but with a Kevlar 49 strength member. This cable had the phenomenally low elastic stretch of only 0.2 of 1% at a working load of 3000 lb. The coax was

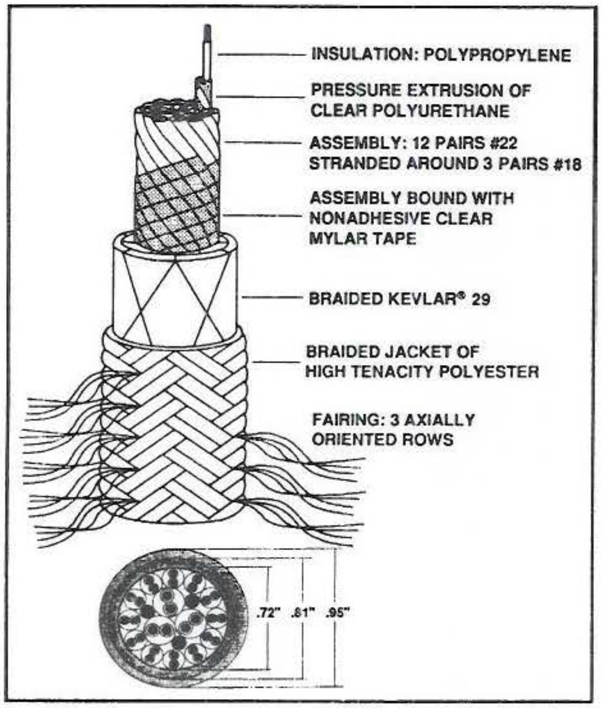

Figure 2. Instrumention cable design.

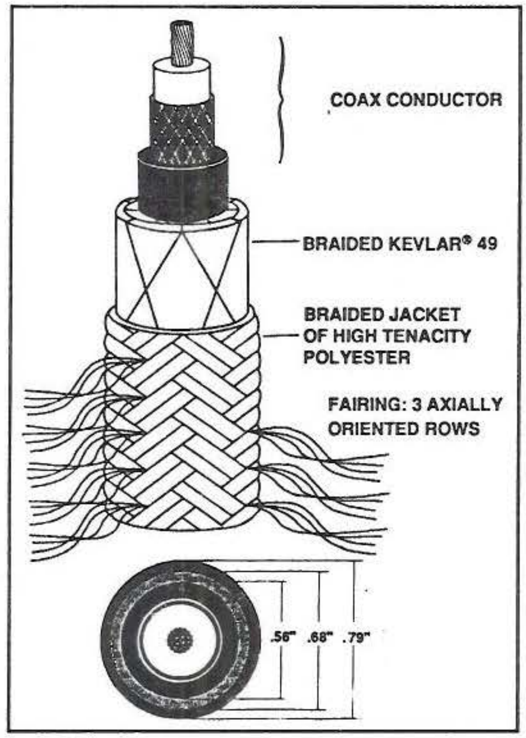

Figure 3. Lead-in coaxial cable design.

overbraided with the Kevlar strength member, and a polyester jacket contained the filament fairing. The resulting total diameter was 0.79 in.

The third essential component for the system was 9100-m length of spaced armor coaxial umbilical cable (Figure 4). This cable had a modest in-water weight of 1.0 lb/m, a measured break strength in excess of 21,000 lb, a near-linear torque of only 21 in-lb at 10,000-lb tension, a nonrecoverable stretch to 10,000 lb. of 0.2 of 1%, and an elastic stretch of 0.5% at 3000 lb and approximately 1% at 10,000 lb. (These numbers are given for comparison with its Kevlar counterpart.) This cable, in addition to providing the communication link, was used repeatedly to lower anchors to the sea floor, to go slack without kinking, to release the anchor, and to be recovered. The anchor was occasionally pulled out of the mud and raised to the surface, which produced tension with approximately 75% of yield. A second cable was taken as a spare but was not used.

Buoyancy

The legs were rendered slightly positively buoyant by using 110 clamp-on syntactic foam blocks distributed along the lengths of the legs. A low-density (37-lb/ft^3 buoyancy) foam is used to a depth of 2000 m, and a higher density (29-lb/ft^3 buoyancy) foam is used at greater depths. Each foam block was 2 ft^3 in size. The result of this flotation was to render each leg about 850 lb positively buoyant. These floats were designed to clamp on the cable, which made attaching and removing the floats quick (approximately 30 seconds) and easy.

The apex buoy used 95 low-density floats of the same design as that used on the legs. The apex floats were contained in an aluminum cage that measured 7 ft × 7 ft × 4 ft and resulted in 6150 lb of buoyancy. A radio beacon and a light flasher were activated when the buoy was on the surface, and a radar reflector was attached to the buoy.

Mechanical Termination Housings

The top 2150 m of each leg consisted of six identical electromechanical cable sections. The termination points between each section contained either a telemetry multiplexer (three/leg) canister or a mechanical dummy termination. The engineering sensors were also attached at these termination points. The canisters and sensors were enclosed in a schedule-40 polyvinylchloride (PVC) housing for protection during handling, deployment, and retrieval. The PVC housings were bolted at the section's termination points to an aluminum strength member, which served as a load-bearing member for the structure cable tension.

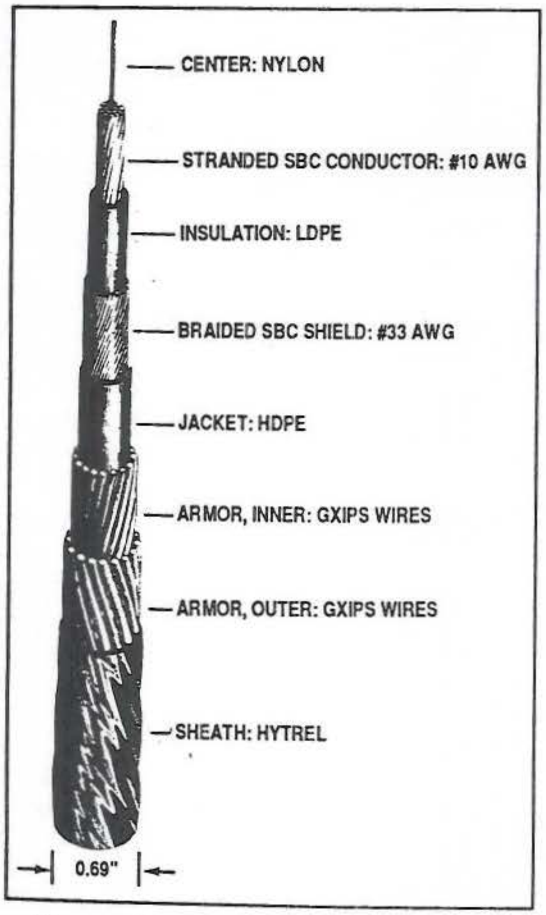

Figure 4. Spaced armor coaxial cable design.

Anchors

The anchors were a basic clump design with 18-in flukes on one end to help prevent dragging, and each weighed 7000 lb in water (Figure 5). The lowering point was positioned so that the anchors would not rotate during deployment. The structure's mooring lines and coaxial cable were attached at the anchors through a pair of acoustic releases/transponders. The communication cable for leg 3 was fairleaded through the anchor for protection and terminated at the anchor with an electrical quick-disconnect connector. The connector kept the cables from flooding during the recovery operation when the anchor was released from the leg.

Special Handling Equipment

Only a minimum of special handling equipment was required beyond that provided by the vessel. A V puller sheave was designed that clamped on the deck capstan and was the primary device used in recovering the neutrally buoyant structure cables. The structure cables were fairleaded to the V puller through a special 4-ft-diameter stern block. The structure legs were coiled in three individual tanks, 8 ft diameter $\times$ 4 ft high, for storage and transportation. The legs were hand-deployed from these tanks. A fourth tank, 6 ft diameter $\times$ 2 ft high, was used to store spare leg sections. The vessel handling equipment will be discussed below.

DEPLOYMENT TECHNIQUE

Vessel Layout and Equipment

The USNS LYNCH was used during the development and testing phase and during the experiment. The LYNCH is 210 ft long and has a 39-ft beam, a single screw, and a bow thruster.

Figure 6 shows the deck layout and how the equipment was arranged. The operation employed two winches, which were part of the vessel's support equipment. The first was a direct drive drum winch containing 7000 m of 3×19 0.5-in

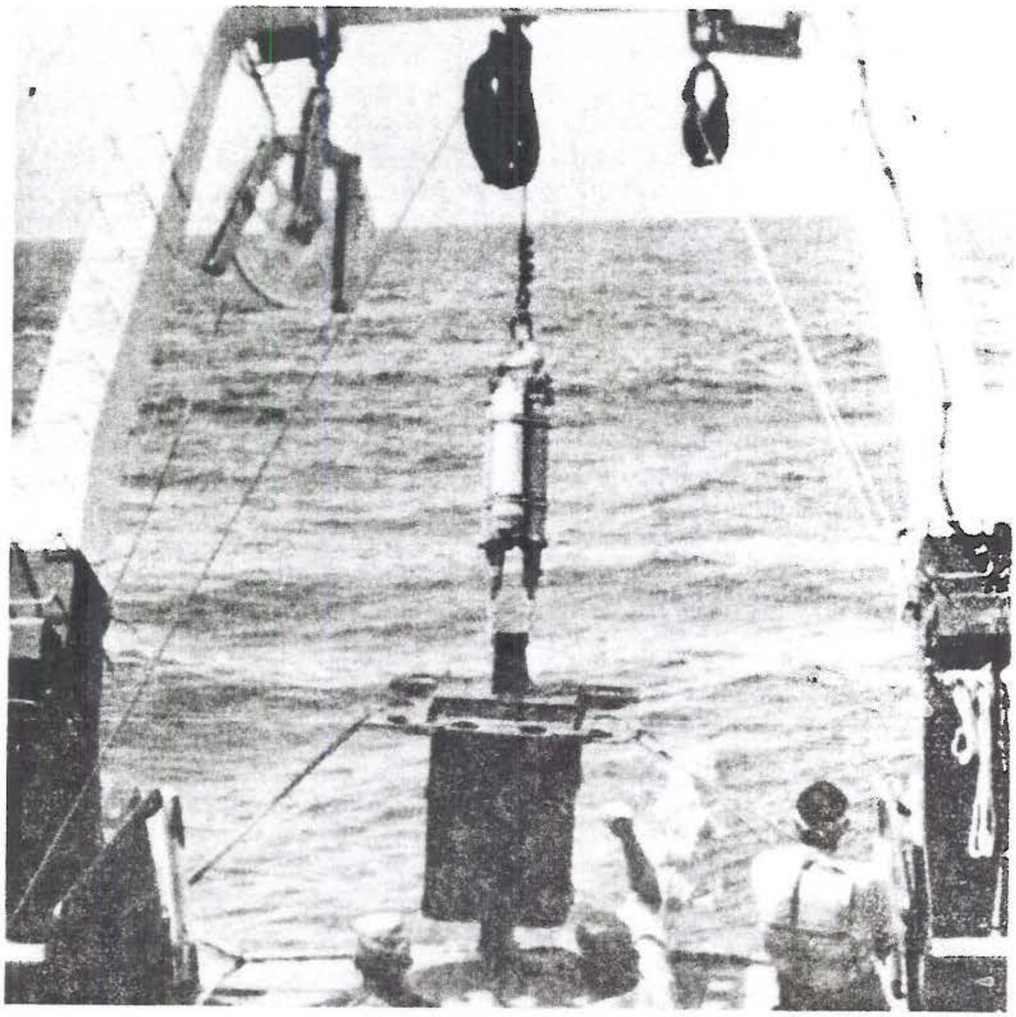

Figure 5. Structure leg anchor.

wire rope. This winch was used to move anchors on deck and to transfer the anchor load to the umbilical cable during the deployment of leg 3. The second winch was a traction winch used for lowering the anchors to the sea floor. This unit had two supply drums available, and each contained 9100 m of the coaxial umbilical cable.

In addition, instrumentation was provided for measuring cable-out and tension. A stern U-frame was used for overboarding large loads, the apex buoy, and the anchors. The structure's leg flotation blocks were stored in the hold below the main deck area.

Deployment Scenarios

The major constraint on the deployment plan was the requirement to deploy the entire system from the 26-year-old LYNCH, using only existing deck and winch equipment. This problem was further aggravated by an ever-changing crew, who in most cases were not familiar with the deployment procedures or the technology involved.

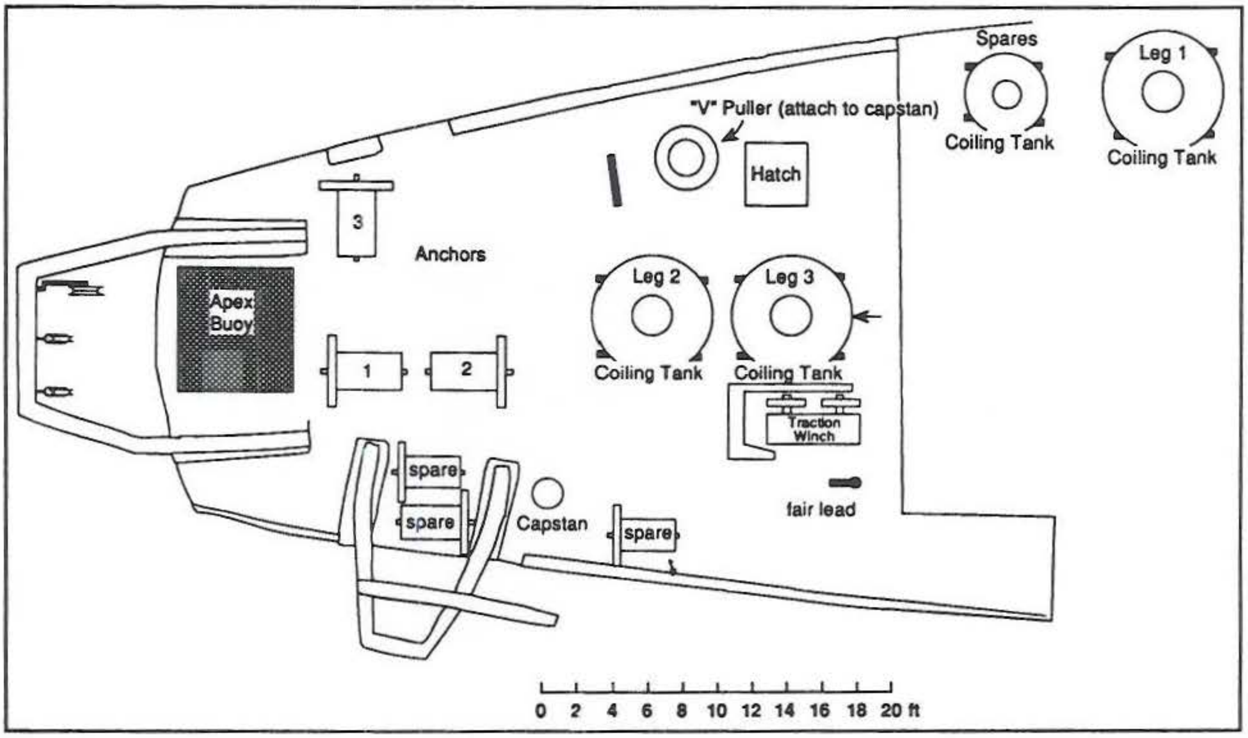

Figure 6. Deck layout.

Other problems were a small deck space of only 28 ft × 40 ft, a maximum payload-carrying capacity of about 70 tons, and no at-sea deck-service crane.

The solution to employing this vessel was a simple deployment plan made possible by the mooring components described in the previous section. Central to the plan was coiling each leg, completely made up and tested, in a coiling tank. Thus, to deploy a leg, the instrumented cable was payed out from the tank by hand on demand as the vessel proceeded down the track at approximately 1 kt. The syntactic foam blocks were clamped on along the way, which in turn floated the cables and in the process avoided the need for holding-back machinery. Instruments thus attached to the cable did not have to negotiate winches, capstans, or other conventional cable-handling equipment.

Figures 7–10 depict the deployment and recovery scenarios.

Deployment Scenario–Leg 1 (Figure 7)

The environmental assessment[2] of the area predicted the prevailing weather would be out of the southeast; therefore, the planned orientation would result with leg 3 and the tending vessel down weather in the northwest quadrant. This assessment also identified the potential for an oceanographic front, a subtropical front, to meander through during the experiment period. This front would manifest itself with currents in a direction different from the historical prevailing currents and with surface magnitudes up to 1.2 kt.

This front did appear in the area and required that the moor be rotated clockwise 120° to put leg 3 near down-current. This rotation placed leg 3 in an east/west direction and the tending vessel due east of the moor. This high current persisted for most of the period but did not cause any insurmountable problems. Figures 7–10 can be

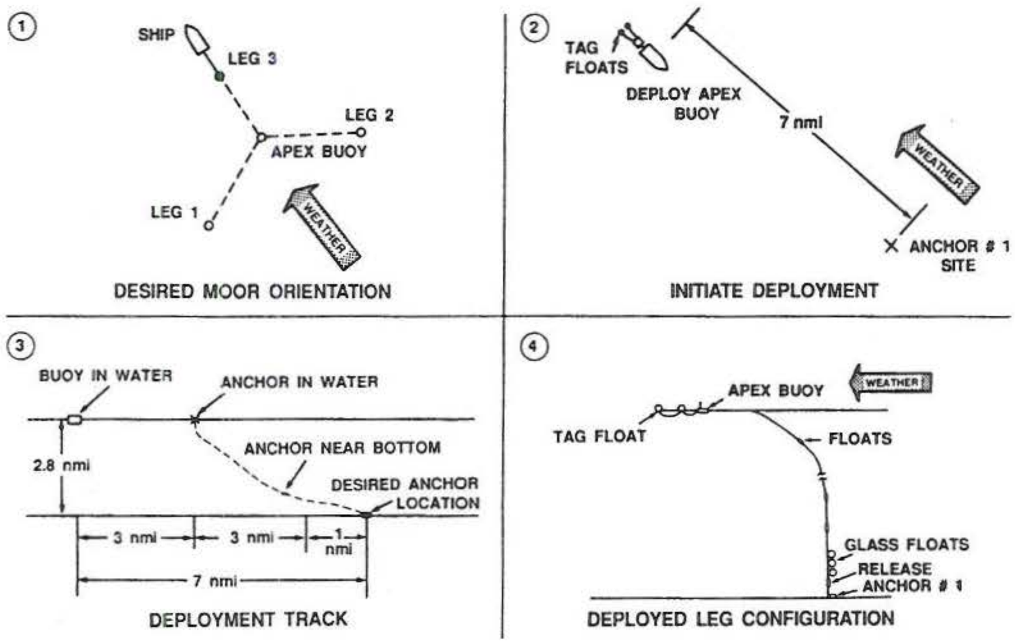

Figure 7. Deployment scenario, leg 1.

viewed with north still at the top on the plan views, but the moor and weather rotate 120° clockwise.

The leg 1 deployment was initiated 7 miles down-track by placing the apex buoy in the water and by paying out the leg on demand as the ship proceeded at approximately 1 kt up-track. The ship slowed and the tension was held, usually by hand, while the foam flotation blocks were rapidly placed at their premarked locations. The ship then continued down-track. Once the leg was deployed and floated on the surface, the anchor was hoisted into the water via the U-frame and lowered at approximately 1 kt. As the anchor neared the bottom, the ship maneuvered it in place with the aid of information from the anchor navigation system. Once on the bottom, the lowering cable was released via an acoustic release and recovered while the deck was being prepared for the next leg deployment. Figure 7 shows the final deployed configuration.

Deployment Scenario–Leg 2 (Figure 8)

The second leg was deployed similar to leg 1. This leg was the most difficult of all the legs to deploy. The ship had to maneuver with the winds and generally the currents off the starboard quarter. This required good ship control to assure not being blown off-track while arriving at the desired site with the anchor near touch-down.

The second leg was attached to the apex buoy, which was now moored via the first leg in a single point moor and tending down-current. The ship then proceeded in the mandatory direction, paying out cable and then lowering the second anchor in place. In the process, approximately 11 miles of cable (two legs plus the lowering wire) were swept through the 3-mile-deep water column. Because of the high drag, relatively low breaking strength, and lack of gravitational catenary on the cables, this had to be done in a very careful,

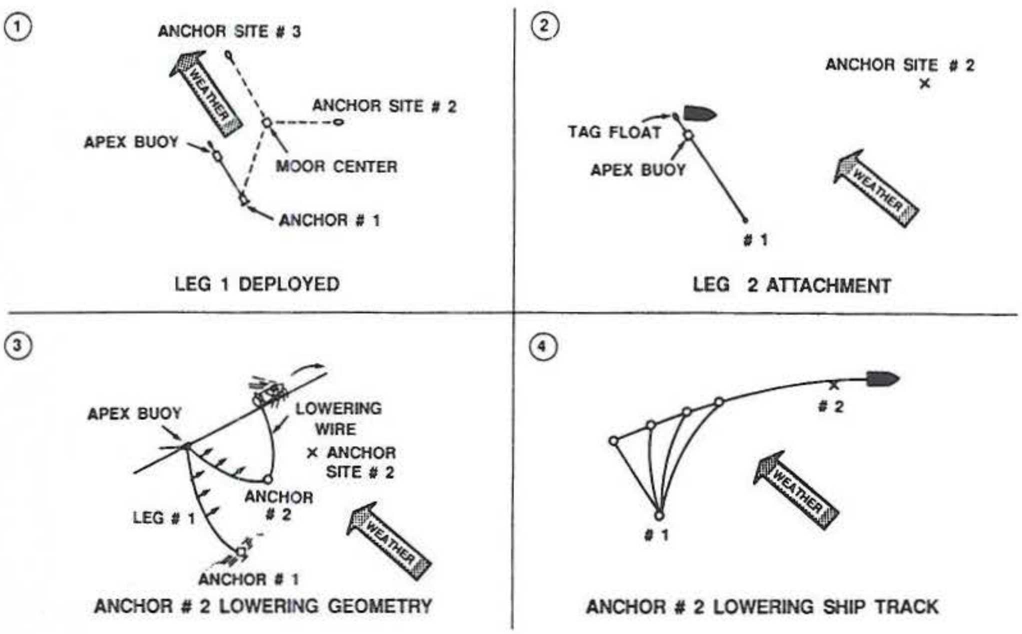

Figure 8. Deployment scenario, leg 2.

time consuming fashion. Excess speed could part the cable and also submerge the apex buoy, which would increase drag.

Deployment Scenario–Leg 3 (Figure 9)

The third leg deployment was initiated by bringing the ship slowly down-track with the tag buoy coming along the starboard side. The tag buoy was brought aboard through the stern U-frame and leg 3 attached. The leg was streamed out while the ship proceeded at approximately 1 kt. When the leg was fully deployed on the surface, the anchor was hoisted in the water by the drum winch until the tension was transferred to the previously attached umbilical cable. The apex buoy should be on the surface near moor center and leg 3 stretched out on the surface, with the leg 3 anchor beyond the touch-down site at the time of overboarding the anchor. A combination of stern and bow thrust and prevailing weather was used to maneuver the ship to the desired touch-down point while the anchor was being lowered. A radio beacon on the apex buoy signaled when the buoy was submerged and depth sensors indicated the apex depth. Once the anchor was committed to the bottom, the ship proceeded down-track approximately 2 miles, laying umbilical cable on the bottom. At the end, the ship slowed, secured cable payout, and proceeded into a stern moor for the duration of the experiment.

If a ship tends back into the moor or if weather increases to the extent that the mooring load becomes excessive or the ship moves out of the allowable watch zone, the engine is utilized to alleviate the condition. If a storm or other events require, the ship can release itself from the third anchor via an acoustic release and recover the umbilical cable, leaving the moor intact.

Recovery Scenario (Figure 10)

Recovery was initiated by hauling in the umbilical cable; rolling the third anchor out of the mud; and recovering the umbilical cable, anchor, and

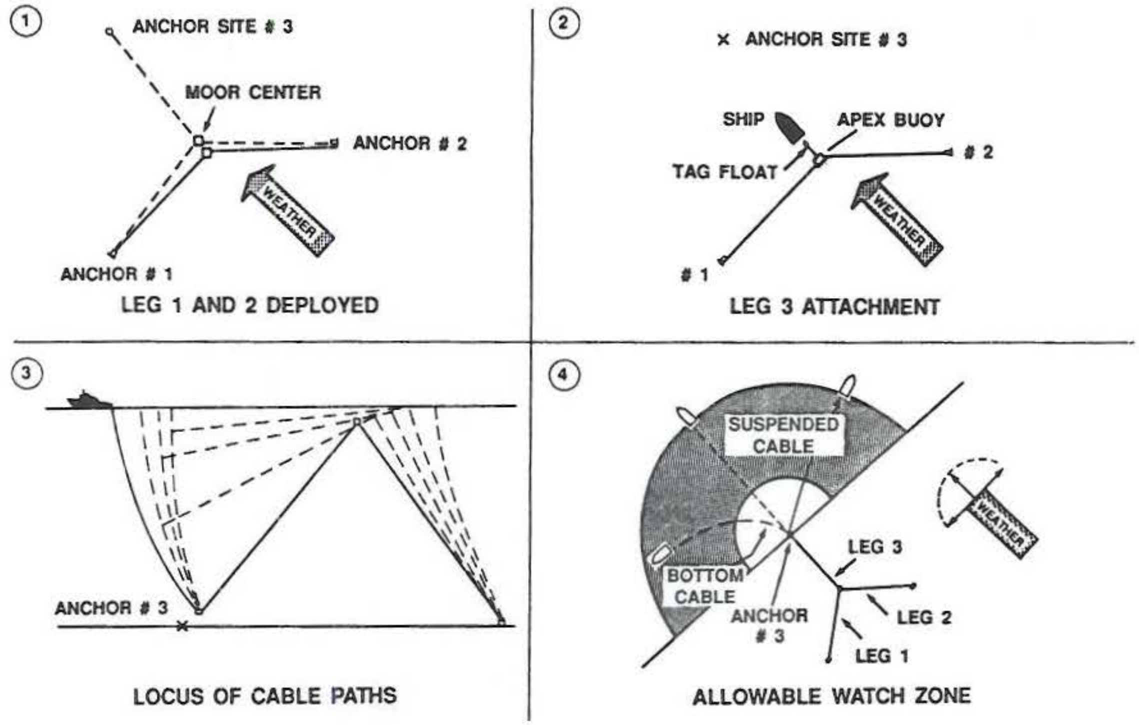

Figure 9. Deployment scenario, leg 3.

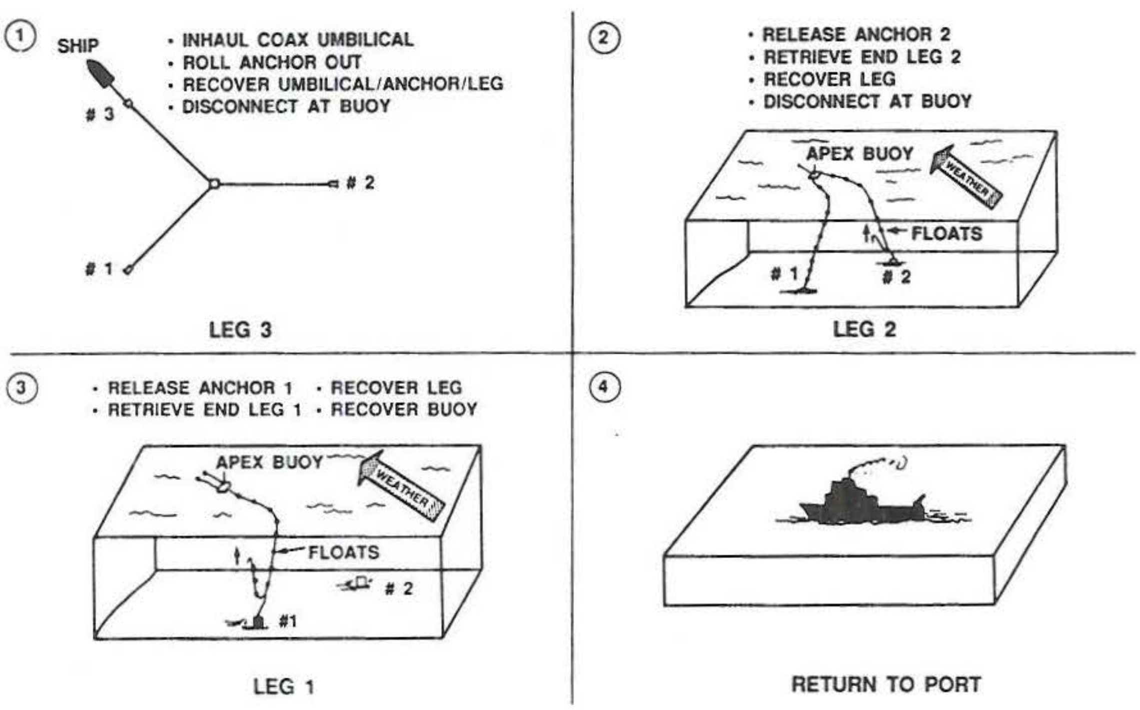

Figure 10. Recovery scenario.

leg 3 cable until the apex buoy was reached and detached. Leg 2 was recovered by activating its anchor release and retrieving its lower end for leg recovery once it reached the surface. Leg 1 was done in the same manner. However, when the apex buoy was reached, it was hoisted aboard via the U-frame and deck capstan. Once the apex buoy was aboard, the ship returned to port. The deployment and recovery process required approximately 3 days each.

CONCLUSION

A large moored tripod oceanographic measurement structure was fabricated and successfully deployed and retrieved in the deep ocean. This success can be attributed to a technology base that allowed use of light-weight structure components. These components were combined in a configuration that was easily deployed from a single, relatively small, oceanographic research vessel. The results of this effort provide the Navy with a valuable asset for future operations.

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